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An isentropic analysis including frontogenesis

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AN ISENTROPIC ANALYSIS INCLUDING FRONTOGENESIS

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and
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AN ISENTROPIC ANALYSIS INCLUDING FRONTOGENESIS

BY

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1927

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1928

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I Introduction

In November 1936 there developed over the United States a weather situation which was a despair to the synoptic meteorologist who depended solely upon the surface weather map. By the use of surface indications alone in this problem it was difficult to visualize just what was taking place in the atmosphere, and it was more difficult to predict, with a comfortable degree of confidence, the future development of the weather. It is the purpose of this paper to take this weather sequence which presented a perplexing problem to the surface map analysist and examine in detail the upper air data with the object of finding a clue to the causes of the development of the situation, and further, to investigate the possibility of having made a reliable forecast in the light of such analysis. The period covered is November 22-24 (inc.), 1936.

In order to investigate and coordinate the upper air data the following tools of analysis are used: isentropic charts, selected vertical cross sections of the atmosphere and 24 hour pressure change maps for the surface. The usual 8 A.M. surface maps plus the 8 P.M. map for the 23 rd are also included.

II General Weather Situation

A very brief description of the weather situation will now be made with the understanding that a more complete analysis of pertinent features will be included in the detailed day-by-day study. Our chief interest lies in a cyclone which developed as a secondary of a main disturbance over the Dakotas on the 22nd, lay over Illinois on the 23rd and on the 24th swept over southern New England giving that region moderate snowfall, the first snow of the year at many points.

Map #2 shows the general weather situation on the morning of November 23, 1936 which is the midway point in the situation investigated. Over the northeastern part of the United States there has been an invasion of Pc air which has given that section unseasonably low temperatures. Over the southeastern part of the country there is Npc over which Tg is beginning to advance northeastward from the west Gulf region. From the Pacific Pp has penetrated to and including the Rocky Mountains.

The cyclone centered over Springfield, Illinois originated as a secondary of a main disturbance which lay over the Dakotas 24 hours previously. As will be seen, the cause of the secondary formation was advection of relatively warm air aloft. The effect of this less

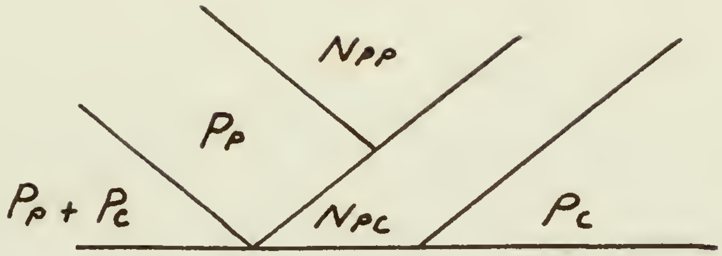
dense air is beginning to be felt at the surface on the morning of the 22nd. On map #1 the contour of the isobars over Nebraska and South Dakota is suggestive of a secondary formation. As experience has shown, a secondary is usually formed as the result of a wave on a quasi-stationary cold front, or occasionally one is formed at the junction of a warm and cold front of an old occluded cyclone. But cyclogenesis in this example appears to belong in a different category.

The P.M. surface map of the 22nd not included in this report, shows that the secondary has dominated the primary disturbance and taken over the energy of the system. In fact the primary has all but disappeared at this point.

The pressure tendencies around our cyclone on the morning of the 23rd show that on the whole they are positive and from this it would appear that the disturbance is filling up. However, the indications at the surface are masking the activity aloft and, by following the weather sequence it is found that the system moves along with undiminished intensity. A supply of Tg air at upper levels, it is found, has supplied enough energy to maintain the system. It is further discovered that this supply of warm, moist air is cut off from its source which fact would indicate that the disturbance would not intensify much more. Map #3 for the 23rd P.M. and map #4 for the 24th A.M. show this to be the case.

The only fronts with which we are concerned in this investigation are those associated with the disturbance discussed above. On November 21st an occluded front entered the continent from the Pacific in the region of Sitka, Alaska. As suggested by surface indications and checked by upper air data, this occlusion was of the warm front type with an upper level cold front (1). This frontal pattern swept southeastward until, on the morning of the 23rd we find the occlusion extending from Fort Worth northeastward into the center of our disturbance. The position of the upper level front at this time is approximately parallel to that of the occlusion and lies in advance of it. Presumably, the warm air trapped aloft ahead of and above the upper cold front is dry Npp since there has been no measurable precipitation associated with the advance of the system. However, on the morning of the 23rd advection of Tg has increased the moisture content of the air displaced by the upper cold front sufficiently to give active precipitation over east Texas and parts of Louisiana and Arkansas. A front separating Pc and Npc and inactive from the standpoint of precipitation extends from the cyclone center southeastward through eastern Kentucky on the 23rd A.M. As will be shown, intensification of this front takes place on the 23rd. Frontogenesis also becomes active at, roughly, the position representing the intersection of the occlusion surface with the ground. From this position our new cold frontal surface slopes up and back toward the west. The following sketch illustrates the frontal structure on the

23rd A.M. if an east-west section were passed south of the cyclone center:



The question still remains: Can the situation at the surface be explained by an analysis of upper air data and can such analysis aid in predicting the future weather? But first a word on isentropic analysis.

III A Brief Description of Isentropic Analysis and Technique of Application

Before proceeding with the study of the upper air data it is considered appropriate at this point to review, in a very abbreviated fashion, isentropic analysis and its application to the daily weather situation. This section may well be passed over by those thoroughly familiar with the subject. For those not so conversant, it is hoped that a brief review will help to throw light on the analysis to be undertaken in Section IV.

Professor C.G. Rossby is chiefly responsible for the development of isentropic analysis. A study of references (2,3,4) written by Rossby would be greatly beneficial to those interested in the subject. An illuminating example of such analysis by J. Namias is listed in reference (5).

In the atmospheric layers well removed from the surface, processes are approximately adiabatic. This means that individual particles tend to maintain at constant value their entropy and hence potential temperature. Therefore if a particle moves, its motion is confined to the isentropic sheet whose value of potential temperature is the same as that of the particle.

Non-adiabatic processes include radiation and condensation (evaporation). Radiation is a very slow process in the free atmosphere. Even at moisture discontinuities the process is relatively slow. Condensation is limited to fairly small areas along active fronts and to regions of penetrative convection. These non-adiabatic phenomena do not invalidate the utility of the isentropic concept but should be kept in mind and allowances made when applying the principle to actual cases.

Another relatively conservative property of an individual particle is its specific humidity. This property is used as an indicator in following the movement of the various particles within the isentropic sheet. The winds are also useful in following the particles' trajectories.

It is apparent that an isentropic surface is not a surface of equal altitude. Mean values of potential temperature (θ) throughout the atmosphere indicate that the θ surfaces on the average slope upward toward the poles. On the other hand, mean values of specific humidity (q) show that the q-surfaces generally slope upward toward the equator and that the slope angle decreases with elevation. Of course the contour lines of θ and q for any one day may vary widely from the mean.

Isentropic mixing, i.e., mixing of the particles within the isentropic surface, is often an active phenomenon. The intensity

of such mixing is, Parr suggests, a function of the vertical stability (6). The relative velocities of the air currents similarly affect the intensity of mixing. If an air current is moving relative to an adjacent body of air it will transfer some of its momentum to the other mass through shear and drag effects, causing supergradient winds in the relatively stationary body and itself receive a subgradient wind as a result of the interactive exchange between the two masses. As stated, this Austausch is extensive and takes place on a much larger scale than does vertical mixing. The order of magnitude of this ratio is 50,000:1. Exchange is not limited to momentum but applies to other properties of the air masses involved, especially specific humidity.

Briefly an isentropic chart is prepared as follows: Data are obtained from the various aerological stations. A suitable θ -surface (isentropic surface) is chosen so that it is low enough to show moisture differences clearly and yet not low enough to suffer from the non-adiabatic and turbulent influences of the ground. The height of the surface (Z) and its moisture content (q) over the aerological stations are interpolated for from the data and entered on the usual surface map. The winds at the various heights over the aerological stations are entered. Height lines(dashed lines) are now drawn for every 500 meters altitude. With the height of the θ surface tentatively established at all points, winds from all pilot ballon stations can now be entered. Lines of equal q (full lines) for every

one-or two-gram values are then drawn. Care must be exercised in drawing Z and q lines because of the scantiness of data obtained from relatively few aerological stations. There is no unique solution but a multitude, most of which would be entirely misleading. Considerations set forth later may be used as a guide in developing the technique.

The isentropic chart is drawn in conjunction with the cross sections so that the two harmonize to give the most probable solution. A cross section is a vertical section of the atmosphere taken through aerological stations that lie roughly on a straight line. Over each station q and θ values are entered at the corresponding height of the significant points. Lines of equal θ for every 5° together with lines of equal q are drawn. Winds are entered at the proper levels and in such a way that their direction is oriented with the relative position of the stations. For instance, for a section going from north to south reading from left to right, an east wind is plotted as blowing from the top of the diagram. As indicated before the lines on both cross sections and isentropic chart are adjusted to agree with each other.

Other data entered on the isentropic chart are relative humidity and when desirable, pressure change between consecutive 5° isentropic sheets. The latter quantity is usually taken as the differ-

ence in pressure existing at the isentropic surface selected and the one 5° below it. This gives an idea of the mass of air contained in the layer at various points. The greater the mass, the less is the stability within the layer. When compared with the same data for the previous day one gets an estimate of the mass change within the layer, i.e., convergence or divergence of mass. If no non-adiabatic processes have taken place, the total change in mass throughout the layer encompassing the earth should be zero. However, it varies considerably from point to point.

The following tentative conclusions regarding isentropic analysis have been made by C.G. Rossby (3):

" 1. Isentropic flow patterns are simpler than corresponding frontal patterns on the ordinary weather map.

2. Isentropic flow patterns appear to be fairly stable and change only slowly from day to day. This stability should be of potential value in forecasting.

3. Lines of constant specific humidity and contour lines are nearly, but not quite, parallel. It appears that regions of vertical motion may be determined from the intersection of these two sets of lines on the isentropic charts; the regions of marked ascending motion thus indicated seem to coincide with the precipitation areas on the corresponding ordinary surface weather maps.

4. The flow patterns indicated by successive lines of constant

specific humidity and successive contour lines agree in a general way with the observed wind distributions but,-

5. Isentropic tongues of maximum or minimum moisture content advance less rapidly than one should expect from the observed wind distribution, indicating intense mixing between the tongues and their environment.

6. The weight of a layer enclosed between two super-imposed isentropic surfaces may be expressed through a set of lines for constant weight. These "isobars" are approximately parallel to the stream lines on the isentropic charts and may be used for determinations of convergence and divergence.

7. The isentropic current systems analyzed up to the present time display a pronounced tendency to break up into large anticyclonic eddies."

IV Upper Air Analysis of the Weather Situation

For the upper air analysis the following charts are presented:

Isentropic charts are drawn for $\theta = 300^\circ$ and $\theta = 285^\circ$. Since the air mass contrasts with respect to temperature are so large in this situation it follows that the height of an isentropic surface varies considerably. In some cases the 300° surface is too high to show clearly the moisture distribution and for this reason the 285° surface is added. Despite the fact that the latter goes into the ground in some areas it is employed to show the moisture distribution at the lower levels.

There are four sets of cross sections of which two are north-south and two are east-west:

North-South	North-South	West-East	West-East
Fargo	Sault Ste. Marie	Oakland	El Paso
Omaha	Detroit	Salt Lake City	San Antonio
Oklahoma City	Dayton	Cheyenne	Shreveport
San Antonio	Nashville	Omaha	Montgomery
	Montgomery	St. Louis	
	Pensacola	Dayton	
		Washington	
		Lakehurst	
		Boston	

In addition, surface 24-hour pressure change maps are included since they are helpful in the construction of isentropic charts. In general, an isallobaric high indicates an invasion of cold air and consequent raising of the Θ-surface while a low signifies the opposite.

In the discussion of the various charts and maps, only the features pertinent to this analysis will be examined.

November 22nd A.M.

On the surface map #1 for this date a body of Pc air is seen advancing southward over the central and eastern part of the country, displacing Npc before it. Air of Polar Pacific origin moving southeastward over the northwestern states is also replacing Npc.

Cyclogenesis is active over Nebraska and Kansas with the result that a secondary is forming near the main disturbance which lies to the northwestward. Attention is called to an isallobaric low of (-) 14 over Omaha which suggests the direction of movement of the system/ Surrounding our disturbance are three well formed anticyclones. That containing the Pp air is most notable with a 30.60 center. The Pc high is building up while that in the Npc air mass is slowly weakening.

The boundary between the Pp and Npc is a warm front typ occlusion with an upper level cold front whose structure may be studied in succeeding cross sections. The line of discontinuity between Pc and Npc later becomes the warm front of our forming cyclone.

The 300° isentropic chart, #5, for the 22nd helps to clarify the surface map and, more importantly, gives a clue to the future development. As suspected from the surface system, it reveals an invasion of cold dry air from the north lying east of the Mississippi River. The coldness is reflected in the great height of the surface, and the extreme dryness by the fact that the 1 gram specific humidity line extends to the Gulf of Mexico. The winds and contour lines strongly suggest that this protrusion will extend well into the central United States into which area our secondary disturbance has shown definite signs of entering. The origin of this moisture is presumably the Gulf or the Caribbean from whence it was carried in an anticyclonic eddy to its present position. Another fairly moist band extends from Southern California northeastward over the Dakotas. Its warmth is indicated by the deep trough in the height lines. The winds suggest that this tongue is cut off from further moisture supply of Pacific origin. Moreover, its narrowness renders it susceptible to dissolution through horizontal mixing with the dry air on both sides. Likewise, mixing will tend to modify the dry tongue be-

tween the two moisture bands discussed above. Then too the winds indicate that the dry wedge is retreating.

What relation does this isentropic pattern in the west bear to the system shown on the surface map and what can we reasonably expect to happen? First, we can say that the band of warm air to the northwest on our θ-q chart is an isentropic cross section of the warm air of Pacific origin lying above the occluded front. It appears that the advection of this less dense air leads to cyclogenesis which, in fact, is taking place as surmised from surface indications. But this warm, moist air is in great danger of considerable modification by the dry air on each side of it with the probable result that cyclogenesis will be checked or that even anticyclogenesis will set in unless some other influence is brought to bear. It appears that the moist Tg current will offer this reinforcement. This flow is directed toward the indicated future position of the disturbance center. Hence, it is logical to assume that a fairly well developed center will appear shortly over the central United States.

The 285° θ-surface #6, for the 22nd shows the same features in the eastern part of the country as the 300° surface. In the Rocky Mountains area the 285° chart cannot be used since it intersects the ground.

The 24-hour pressure change map #20 shows a general rise east of the Mississippi which is associated with the invasion of cold,dry air from the north while the isallobaric low in the western part of the country indicates the displacement of one air mass by another of lower density.

The cross sections for the 22nd which were drawn concurrently with the isentropic chart for the same date added further light on conditions aloft. In the El Paso-Montgomery section, #13, the main feature is the moisture inversion over El Paso. The specific humidity increases from 2.1 grams at 1700 meters to 5.3 at 2500. The southerly and southeasterly winds indicate the probable origin of this air as Tg. Adjacent to this moist,current moving northward is a dry current moving southward. The horizontal shear and mixing between the two must be quite intense.

In the Oakland-Boston section, #12, air of Pacific origin is seen replacing one of Canadian origin. There appears to be no sliding up of the Pacific air over the Canadian air since the latter is moving eastward faster than the former. This would seem to account,in part at least, for the lack of precipitation in connection with the occluded front.

The two north-south sections, #11, show the advance of Pc from the

north. In both of these sections convergence is observed in the frontal zone. In the Fargo-San Antonio chart the amount of moisture above the frontal surface is insufficient to give precipitation but there is snow falling just to the east of Sault Ste. Marie-Pensacola section.

November 23rd A.M.

The A.M. surface map for this date, #2, shows that the situation has developed about as might have been expected from the previous analysis. The secondary found on the map for the 22nd now has a closed circulation of its own and the former primary cyclone has disappeared. In fact the map for the evening of the 22nd (not included) shows that the primary had all but filled up at that time.

The southward advance of Pc to the east of the disturbance has been halted and indeed the Pc-Npc boundary has become a warm front within the cyclone. However, Pc is seen pushing southward to the west of the system and the chances for the formation of a secondary cold front appear favorable.

The air of Polar Pacific origin has continued a fairly rapid advance (about 600 miles in 24 hours) and we now find the Pp-Npc

front extending from the cyclone center southwestward to Fort Worth. Aloft and in advance of this position lies the upper level cold front. Behind this front rain is falling over east Texas and parts of Louisiana and Arkansas. From the surface map it is difficult to say whether this precipitation is the result of upglide over the Pp-Npc front or is caused by forced ascent from the advance of the upper cold front. What does appear certain is that Tg air must have come into this region aloft and added enough moisture to give precipitation from a frontal system that heretofore had produced none. The snow falling at scattered points in the Great Lakes region is the result of instability in the Pc air mass which has picked up moisture and heat in the lower layers on passing over the lakes.

Now let us examine the reports from stations in the cyclonic area. We note that the lowest pressure, 29.84 at Springfield, Ill., is practically the same as the lowest pressure (29.82) reported in the secondary 24 hours before. On the evening map of 22 November, 12 hours previous, the lowest pressure reported was 29.72. From these considerations alone it would seem that the system deepened a little and then began to fill. This hypothesis of filling becomes practically a certainty upon examination of the current pressure tendencies in and around the system, all but two of which are positive. If the analysis stopped at this point the forecaster should logically expect the disturbance to fillcompletely in short order and cause no more trouble, at least as far distant as Boston. However

there is a factor in the surface reports that is disturbing to the mind of the forecaster who makes the above prediction and that is the rain to the southwest of the center. This precipitation implies that there is a possible push of Tg air aloft from the west Gulf region and the reported cloud movements from the southwest strengthens this supposition. If this is true and if the warm, moist air reaches the disturbance it might supply enough new energy to maintain or even deepen the system. It is apparent that in working only with the surface map the conflicting indications make the forecaster's job anything but easy. He must turn to upper air analysis to supplement the facts gained from the surface map. Let us now so proceed.

The 300° isentropic chart, #7, for the 23rd displays more moisture contrasts and contains more well defined flow patterns than that for the previous day. The most pronounced feature of the chart is the narrow tongue of moisture which now extends from eastern Texas northwestward, then curves anticyclonically. This tongue, of course, is identified as the one which was just making its presence felt over New Mexico the day before. There has been a general decrease in the height of the surface in the vicinity of the moisture invasion, as is to be expected with the advection of a warm current. In 24 hours the surface over Shreveport has dropped from 2680 meters to 1820; at

St. Louis from 3310 to 2620; at Washington from 4070 to 3350. The dry tongue which, the day before, extended roughly from Lake Erie down to Louisiana has now curled around anticyclonically in its southern portion and has been cut off from its northern source by the tongue of moisture. The northern part of the dry tongue has been translated or shifted eastward and its axis is now off the coast. The two currents, moist and dry, compose an anticyclonic eddy centered roughly over Nashville. The mo ion of the two currents tend to maintain the directions indicated on the chart, but the whole system is subject to translation by the general circulation whose direction in this area is toward the east.

Evidence of the lateral mixing is well illustrated in these two currents. It is to be observed that a "bubble" of moisture over West Virginia has detached itself from the main moisture supply. Narrow tongues of air are subject to intense mixing by surrounding air masses which tend to alter, among other properties, their moisture contents. This is precisely what has taken place. The result of the mixing is such that over Kentucky the air is drier than on either side along the moist tongue axis. The same process has likewise affected the dry tongue. It is seen that off the coast in the region of the Virginia Capes the air in our isentropic surface is more moist than on either side along the dry tongue axis.

The other two bands, one moist and the other dry, which lay to the northwest of our Tg current the day before, have disappeared. As was surmised at the time the previous chart was discussed, interactive mixing has so neutralized them that they are indistinguishable on the present chart. Another possible explanation is that the two moist tongues merged and that the dry one retreated and combined with the large cold invasion that came in from the region of British Columbia and now lies with its axis over Minnesota.

The 285° surface, #8, reflects the indications of the 300° surface. It is to be noted, however, that the Tg current axis in the former is displaced a little to the westward.

The isallobaric highs and lows on the 24-hour pressure change map for this date, #21, coincide nicely with our cold and warm currents respectively.

Let us now attempt to associate the features of our isentropic charts (principally the 300°) with those of the surface map. We can at once that the horizontal penetration of the moist current aloft is much more extensive than would be judged from the surface data. In this flow we have a good source of energy for our cyclone if it continues to feed moisture into the system. If we decide that it will, we can look forward to a deepening of the disturbance and heavy

amounts of precipitation. In conflict with the supposition is the filling tendency in and around our system as expressed by the general rise in pressure. This would suggest that the cold air from the northwest is making its influence felt. At this point we are undecided as to what prediction to make. It depends for the most part on the movement of the cyclone and the movement of the current systems. At the moment our disturbance is partly in one current and partly in another. By noting the relative pressure tendencies and the direction of the warm sector isobars we should judge the movement of the system to be roughly east-northeastward. (The justification for the term warm sector will be made later). By extrapolation and by study of the present flow pattern and the winds it would appear that the two currents should be translated in the same direction as the cyclone and at the same time each curve off slightly in an anticyclonic fashion. Another point for consideration is that our moist current is open to its source of water vapor and should not be destroyed completely by mixing. By mixing with this moisture-rich flow the dry current should gain in water vapor particularly in its adjacent boundary. Hence if our disturbance comes under the influence of the cold tongue it will not be entirely lacking in moisture. Still the situation is a borderline case from the forecaster's standpoint. He hopes that the cross sections will give him definite clues one way or the other.

Fortunately the Oaklan-Boston cross section, #15, passes just south of the cyclone center and furnishes us an excellent picture of the frontal structure. We note first the warm front separating Pc and Npc and the differences in temperatures in these air masses. Now consider the warm front type of occlusion with the attendant upper level cold front. We see that the order of warmth of the air masses involved is Npp, Pp and Npc which would result in the placing of the fronts as drawn. A cold front intersecting the ground has appeared in approximately the position where the occlusion meets the ground. This is the result partly of advection of cold Pc down the western side of the cyclone. Another contributing cause is cooling of the air by evaporation. The pilot's remarks during the morning ascent over Omaha stated that it was snowing and raining aloft and yet only a trace was reported at the surface. The relative humidity on the 285° θ-surface over Omaha is 100% whereas it is much lower at other aerological stations in the general vicinity. Thus it is logical to suppose that cooling by evaporation was not an inconsiderable factor.

The El Paso-Montgomery section, #16, shows the same general features as the one for the previous day. The only modifications are that the moist air flow is now richer in water vapor and that the area of maximum moisture is closer to the ground.

The Fargo-San Antonio section, 714, takes a north-south slice through the dry and moist currents and aside from giving us our three dimensional picture from another angle throws no new light on the situation.

On the same chart, the Sault Ste. Marie-Pensacola cross section is very enlightening. Before examining it a word about a recent idea of Professor Rossby's should be appropriate. The idea is subject to further investigation and has not yet been published. Only the conditions of the problem and the results will be stated without going into the demonstration. Given a north-south section through the atmosphere with potential temperature surfaces sloping as shown in figure 1 and the winds westerly aloft and at the surface. Now assume that under conditions that may be demonstrated as possible the surface west wind to the south increases or remains the same, but that in going from south to north the surface west winds decrease or even shift to the east. Then the Θ-surfaces will

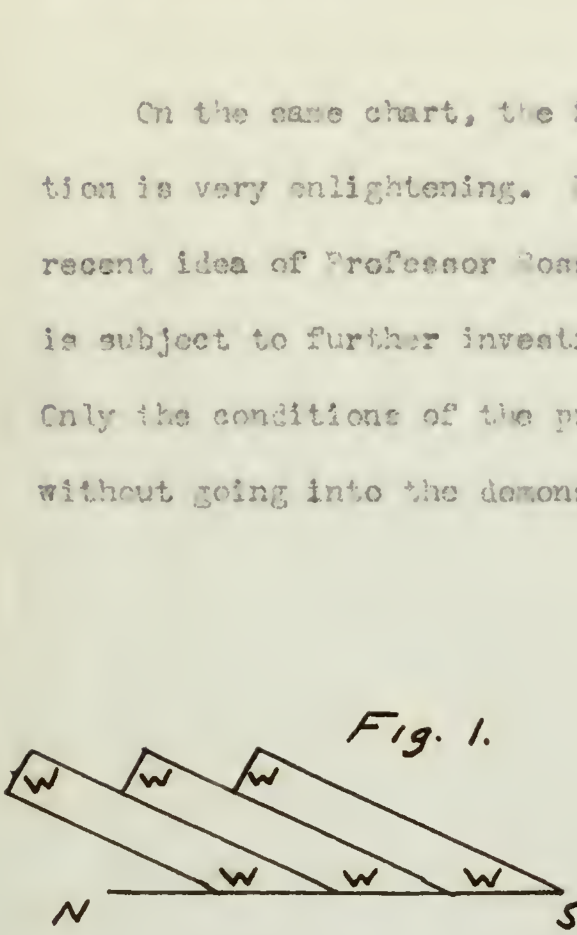


Fig. 1.

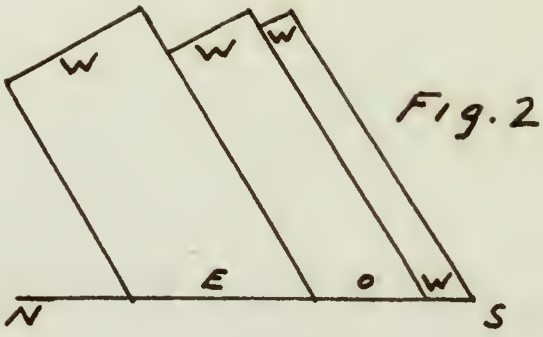


Fig. 2.

tend to arrange themselves as shown in figure 2. The surfaces have increased their slope and there has been a packing of the surfaces to the south and a greater spacing to the north. A packing of the Θ-surfaces and a steepening of their slope is associated with frontogenesis which of course includes frontal intensification.

An examination of the Sault Ste. Marie-Pensacola section reveals that approximately these conditions are being fulfilled in the region of our warm front. Hence we may expect intensification of this front. At any rate we note considerable convergence in this zone which is suggestive of frontogenesis. Furthermore, the moisture content here has increased in the last 24 hours as seen on the 300° surface and there is a strong suggestion of up-slope motion as displayed by the contour lines of specific humidity and height. The relative humidity over St. Louis on the 300° map is 39% while over Dayton it is 71% which fact further strengthens this supposition. But the Sault Ste. Marie-Pensacola cross section shows that the moisture distribution most intimately associated with the warm front lies in layers below the 300° surface. The 285° surface, according to this cross section, shows a representative distribution of the specific humidity lines. We also note in the contour lines of specific humidity and height on the 285° surface a strong suggestion of up-glide motion by moisture in our frontal area. The relative humidities here again bear out this idea. Going from Nashville to St. Louis to Dayton the relative

humidity increases from 48% to 56% to 65%.

Now that we possess the additional information of frontogenesis in connection with both a cold and warm front our way is made much clearer. We now have a true wave disturbance notwithstanding the fact that the structure aloft is rather complex. It is now logical to predict that this system will move fairly rapidly in the direction indicated by the warm sector isobars.and by the relative pressure tendencies. Since the moisture content in this area, particularly in the lower layers, shows signs of increasing as well as tending to move up-slope and since our warm front is intensifying we should expect a precipitation should start shortly.

Let us now decide whether the system will deepen or fill. Behind the cold front the winds are moderate to fresh and since the movement of the front is unopposed by any pressure gradient we should expect the cold front to move fairly rapidly. On the other hand, the motion of the warm front is directed against a fairly good pressure gradient. It appears certain then that the system will occlude. The occlusion process will tend to deepen the systdm as opposed to its present filling tendency caused by the advection of cold air. These two conflicting forces cause us to decide that the system will approximately maintain its present intensity. What, then, should a forecaster in Boston, say, expect for his area from this system. Taking the

above analysis all in all, he could logically expect some snow but not a very violent storm. Whether the system will pass to the north of that station or to the south is impossible to say at this time.

November 23rd. P.M.

On the surface map, #3, for this period we note that the developments have taken place in general along the lines expected. The cyclone has maintained its intensity or possibly has filled slightly. The direction of motion of the system has been a little to the east of that predicted which would suggest that the storm center will now pass to the south of Boston. The pressure tendencies substantiate this assumption. A warm front type of precipitation has started which has been in light amounts only so far.

An interesting feature of this map is the cessation of precipitation to the southwest of the center. It is difficult to explain this from the surface map alone but if we go to the 300° isentropic chart, #7, for this date the answer becomes more apparent. At that time the broad island of dry air extending from South Carolina to Mississippi is seen curving into the rain area in an anticyclonic fashion. It is evident that this dryness is responsible for the cessation of rain. Going back to the P.M. surface map we note evidence of a wave disturbance forming over the east-

ern Gulf region. Hence we can expect that precipitation will soon resume in the Gulf states.

November 24th. A.M.

The surface map, #4, for this period shows our disturbance centered over Rhode Island with a lowest pressure of 29.84 which is about the same as it was 24 and 48 hours ago. The system has traveled approximately 1000 miles in 24 hours which indicates a speed a little in excess of that anticipated although the wave character of its frontal pattern suggested that its movement would be rapid. Snow is still falling as a result of warm front action.

In the Gulf of Mexico we note that the new wave disturbance has continued to develop and that rain is again falling in the Gulf states.

The other features of the map, while interesting, are not pertinent to the analysis and will not be examined.

On the 300° surface, #9, for this date we find that the rapid movement which has characterized our current systems has continued. The axis of the moist current which we have been

following now lies off the coast. The moisture found in the vicinity of our disturbance is quite low which suggests that the snow is falling from lower levels. The dry current which, the day before, lay over Minnesota is now over West Virginia. Through mixing, a dry "island" over New Mexico and Colorado has been detached from this same dry tongue.

The 285° surface, #10, shows the currents at lower levels. It is observed that the moisture in the vicinity of our disturbance is richer than in the 300° surface and that there is no dry "island" detached from the dry current source. Aside from these minor variations the other features of concern in this investigation are the same.

The Oakland-Boston cross section, #18, reveals the up-slope distribution of the moisture between Washington and Boston. Over the latter station the specific humidity increases from 2.2 grams at the surface to 3.1 at 1300 meters.

The other cross sections for the 24th., #17 and #19, do not intercept the disturbance with which we are concerned. They are included to make the series complete so that if one is interested in other features of the situation he might well wish to use them for reference.

V Some Interesting Features of the Upper Level Pressure Maps.

A cyclone that extends well up into the atmosphere is ordinarily the "cold core" type composed of a more or less homogeneous air mass circulating around a center. This type usually moves very slowly or remains stationary. The disturbance which we have been examining extends upward at least 14,000 ft. but its other properties are clearly different.

An examination of the 5,000, 10,000 and 14,000 ft. pressure maps, #23, #24 and #25, for November 23rd. disclose a well marked warm sector. On the whole, the winds and temperatures fit this representation well. As may be checked by the Oakland-Boston cross section, #15, for the 23rd. the air in the warm sector is Npp, that to the north and east of the center is Pc and that to the west is Pp.

The movement of the center is rapid at all levels. Taking the 10,000 ft. level as an example, the successive positions of the center on the 22nd., 23rd., and 24th. are Montana, Iowa, and the state of New York respectively. In other words it followed the surface Low. The axis of the disturbance at all times was inclined to the northwest.

Further, it is to be noted that the cyclonic intensity was greater at 5,000 ft. than at the surface while at 10,000 and 14,000 ft. it was at least as well marked as at the surface. In this feature it is similar to a "cold core" cyclone but, from the above considerations, it is impossible to classify it as such.

Another point of interest in this investigation is the 24-hour pressure changes at the various levels. Charts #26, #27, and #28 for the 5,000, 10,000 and 14,000 ft. levels respectively on the 23rd. are of significance when compared to the 24-hour pressure changes at the surface. While the latter shows pressure rises in the vicinity of our disturbance all other levels show pressure falls. This can only mean that there has been an advection of warm air aloft and cold air at lower levels and that the effects of the cold air on the surface pressure has more than offset that of the warm air. Further, since the magnitude of the falls increases with elevation up to the 14,000 ft. level it follows that the warm air advection was above that level. Another explanation of the falling pressure aloft is that divergence of mass has taken place.

VI Summary and Conclusions

On November 22, 1936 a secondary disturbance was formed over Nebraska in the southeastern quadrant of a cyclone centered over northeastern Montana. The formation of this secondary was unusual in that it occured in a region which, according to the surface weather maps, was without fronts. The analysis of upper air data for this period has shown that the formation of this secondary was closely associated with the upper level transport of a warm current and, behind it, a markedly colder current of maratime polar air. Thus, the study of the structure of the upper air lead to the insertion into the surface analysis of an upper cold front ---- the advance portion of a warm front type occlusion. This secondary disturbance formed a circulation of its own and soon became the dominant cyclonic system.

On the 23rd. the cyclone moved to a position over Illinois but displayed on that morning a definite filling tendancy. It was ascertained by comparison of the isentropic charts for the 22nd. and the 23rd. that the warm air aloft, which had presumably caused the cyclogenesis, had been modified to some extent by mixing with colder air. The cold air, in contrast to the warm air, was still open to its source and undoubtedly would have filled the system were it not for

two phenomena, brought to light mainly through the isentropic analysis of the upper air data.

First a tongue of moist, warm air from the Gulf of Mexico began to feed the system a new supply of energy. Although this supply was subjected to isentropic mixing with the dry tongue sufficient moisture and warmth were available to contribute to the energy of the cyclone, and possibly to enter into the condensation process.

The second influence, probably of more significance, was active frontogenesis. This lead to the development of a wave disturbance which could clearly be identified in the surface charts. Through dynamic effects, the potential temperature surfaces in the vicinity of the cyclone's warm front were inclined at a greater angle to the ground, and a packing of these surfaces took ;lace. In this manner the warm front was intensified. In addition, a cold front at the surface was formed by advection of cold air of Canadian origin and by evaporation of falling snow in the air behind the occluded front. These two fronts formed a wave cyclone which traveled rapidly to the east. It should be emphasized that the frontogenetic process was discovered primarily in the upper air data through an isentropic analysis.

The cross sections showed that the basic isentropic chart for a

potential temperature surface of 300° was not representative of the lower atmospheric layers wherein the important action was going on. A more representative isentropic sheet for the value of 285° was constructed, and through this chart it was possible to identify a region in which rapid up-slope movement of air was progressing. The discovery of this phenomenon at the time of the forecast would undoubtedly have lead to a more accurate prediction of the snow which ensued within 12 hours.

Although this disturbance never became very deep (it maintained an approximately constant pressure at the center of 29.82 inches), it extended well up into the atmosphere. Upper level pressure maps revealed that the cyclone was not of the homogeneous "cold core" type but had a clear-cut warm sector up to the highest level investigated (14,000 ft.).

Upper level pressure change maps prove that the advection of warm air took place aloft while that of cold air took place at lower levels. The effect of the cold air was so potent that it completely masked the activity aloft.

As a result of this investigation and from experience gained during the daily map discussion at the Massachusetts Institute of Technology in which the same methods are used that are employed in this thesis, certain facts stand out:

Fewer errors would be made and much less individual judgement would be required in making the isentropic analysis if the number of aerological stations were doubled. It is felt that the placing of the present stations is excellent. If their number were increased considerably the treatment of upper air data could be left less to the imagination of the synoptic meteorologist.

It is observed that during the winter (and the weather situation here analysed approximated winter conditions) the currents of moist and dry air move comparatively rapidly. Under these conditions it is often difficult to predict their positions 24 hours in advance, or even locate the source of these currents on the isentropic charts. If aerological soundings were made every 12 hours it is reasonably certain that weather forecasting would be improved. Under summer conditions the current movements are much slower, and isentropic analysis during this season is found more helpful than in winter. It is believed that it could be made equally helpful in the winter if the frequency of observations were increased.

In order to plot the upper air data in a form suitable for an isentropic analysis, certain computed quantities are necessary. One of these, specific humidity, is transmitted through the standard Weather Bureau Code. Another equally important quantity, potential temperature, is not so provided for. Thus potential temperature must be laboriously computed for all soundings. This greatly delays the preparation of the isentropic analysis. It would be of considerable advantage if these values were computed during the individual evaluations of aerological ascents and then included in the code. Moreover, it would not be difficult for the evaluation corps to send in the characteristic values of specific and relative humidity at one or two chosen isentropic surfaces.

During this investigation the practical use of the isentropic concept has been of great value. It is true that in order to make such an analysis daily with accuracy and despatch a certain amount of experience is necessary. It is also true that experience is necessary in order to develop technique in the use of the Norwegian methods of analysis. Undoubtedly isentropic analysis is a valuable adjunct to frontal methods and is therefore worthy of serious consideration.

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